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Grip aperture and target shape

Based on: Verheij R, Brenner E, Smeets JBJ. The influence of target object shape on maximum grip aperture in human grasping movements. Exp Brain Res, In revision

Introduction

Humans have the capacity to grasp a target object in many different ways. Yet, they show characteristic movement patterns. Differences between movement patterns under different circumstances can reveal how various variables are taken into account when planning a grasping movement. One of these variables is target object shape, the focus of this chapter. It has repeatedly been shown that target object shape influences the maximum grip aperture (MGA) for a certain distance between the final positions of the digits (Zaal and Bootsma 1993; Cuijpers et al. 2004; Eloka and Franz 2011; Hu et al. 1999; Chapter 6).

Several possible reasons have been proposed for why MGA depends on target object shape: because the shape influences the desired precision of the digits' final positions ('desired precision', Smeets and Brenner 1999a), because humans have the objective to avoid collisions between the digits and other parts of the target object than the goal positions ('collision avoidance', Cuijpers et al. 2004; Chapter 2; Chapter 6), or because, if a target object is grasped along its width, MGA is not scaled to the actual width of the target object but to the perceived width ('perceived width', Franz 2001; Franz et al. 2001; Franz et al. 2000) or to the perceived volume ('perceived volume', Chapter 6). In the following paragraphs we will address these four explanations and their explanatory value.

Desired precision

Planning how to grasp a target object starts by selecting suitable positions on the target object's surface, after which the digits are moved towards these goal positions (Smeets and Brenner 1999a). To determine suitable positions on the target object's surface the target object's shape is taken into account to ensure a stable grasp (Cuijpers et al. 2004). Because human movements are variable, the digits will not always end exactly at these selected goal positions. The size of the surface available for digit placement influences how important it is to end close to the selected goal positions. A strategy to increase the precision is to approach the target object's surface more perpendicular, leading to a larger MGA (Smeets and Brenner 1999a). This strategy is used when the movement variability is large, for example in fast movements or movements without predictably available visual feedback (Wing et al. 1986; Jakobson and Goodale 1991), or when the desired precision is large. MGA can therefore be expected to be influenced by target object shape through the size of the surface on the target object available for digit placement and any other variables that influence the desired precision.

Desired precision can explain why oblate target objects (cylindrical target objects from which two parts are removed so that the target object becomes a bar with two rounded sides with small grasp surfaces) are grasped with a larger MGA than full cylinders (with large grasp surfaces) (Zaal and Bootsma 1993) and why slender bars grasped at their ends (small grasp surfaces) are grasped with a larger MGA than disks (large grasp surfaces) (Eloka and Franz 2011). However, it can-not explain why the MGA increases with the length of the axis orthogonal to the axis that is grasped when grasping an elliptic cylinder (Cuijpers et al. 2004) or why MGA scales with target object height but not with target object depth (Hu et al. 1999; Chapter 6).

Collision avoidance

Cuijpers et al. (2004) proposed that the objective to avoid collisions between the digits and other parts of the target object than the goal positions also influences MGA. They based this proposal on an experimental finding that could not be explained by desired precision. They found that when grasping an elliptic cylinder the increase in MGA with target object size depends on the length of the axis orthogonal to the axis that is grasped. They suggested that when elliptical cylinders are grasped by their short axis, the protruding parts of the orthogonal major axis act as obstacles, giving rise to a larger MGA. In the study of chapter 6, the grasping model of chapter 2, in which the idea of collision avoidance is implemented, was used to examine whether collision avoidance could explain why MGA scales with target object height but not with target object depth. In line with the experimental findings the model of chapter 2 predicted an increase of MGA with target object height. In contrast to the experimental findings our model also predicted an increase of MGA with target object depth, although the effect of target object depth on MGA was smaller than the effect of target object height. Collision avoidance can thus partially explain the findings of Hu et al. (1999) and of chapter 6.

Perceived width or volume

One might expect MGA to only scale with the true size of the dimension along which the target object is grasped (e.g. Aglioti et al. 1995; Brenner and Smeets 1996; Haffenden and Goodale 1998), but there is evidence that MGA also scales with the perceived size of the target object (Franz et al. 2000; Franz 2001; Franz et al. 2001). A likely candidate for a dimension to use to scale ones MGA is perceived width. However, it might be that a more generic measure of object size is used, such as perceived volume. As tall objects are perceived as having more volume than lower objects of exactly the same volume (Raghubir and Krishna 1999; Wansink and Van Ittersum 2003), using perceived volume might explain why, while grasping target objects along their width, MGA scales with target object width and target object height but not with target object depth (Chapter 6).

In this chapter we aimed to get more insight into the role of desired precision, collision avoidance, perceived width and perceived volume in influencing the MGA. We performed an experiment in which subjects grasped five differently shaped target objects with the same maximal width, height and depth, and that were grasped with the same final grip aperture. We correlated predicted effects of desired precision, collision avoidance, perceived width and perceived volume on

MGA with the measured values of MGA. The predicted effect of desired precision was based on the variance in the endpoints of the digits. The predicted effect of collision avoidance was based on simulations with the grasping model of chapter 2. The predicted effect of perceived width was based on separate measures of the perceived width of the target objects. The predicted effect of perceived volume was based on separate measures of the perceived volume of the target objects. To evaluate the relative explanatory value of the four explanations we calculated the squared correlation coefficient between the predicted MGAs and the experimentally measured MGAs for each explanation.

Methods

Grasping experiment

Subjects

Nine naive right-handed subjects took part in the experiment (6 females, 3 males) ranging in age from 22 to 44 years (mean=30 years, SD=7.7 years). The experiment was part of a program that was approved by the local ethics committee. Before participating, subjects signed an informed consent form.

Experimental setup and procedure

The experiment consisted of a grasping task performed with free vision. Subjects sat on a stool. At the start of each trial their hand rested on a table and their index finger and thumb were touching each other at a starting position located 20 cm to their right and 10 cm in front of the center of their trunk. They were presented with a wooden target object, which was placed on the table, 40 cm in front of the starting position (Fig. 7.1).

There were five different target objects. The expected effects of desired precision, collision avoidance, perceived width and perceived volume on MGA differed for this set of target objects. We used a cube ('cube'), a three-dimensional plus sign ('plus'), a rectangular block ('block'), a cylinder ('cylinder') and a sphere ('sphere') (Fig. 7.2). The dimensions and orientation of each target object were such that its maximal height, width (the dimension along which the target object is grasped), and depth (the horizontal dimension perpendicular to the width) were all 6.0 cm. The 4.24 x 4.24 x 6.0 cm 'block' was grasped by the 6.0 cm long vertical edges that were 6.0 cm apart. The 'plus' was made of 6.0 cm beams with a cross sectional area of 0.76 x 0.84 cm. The area available for digit contact was much smaller for the plus and the block than for the cube, the cylinder and the sphere. The masses of the objects were 149, 7, 76, 111 and 80 g for the cube, plus, block, cylinder and sphere, respectively. Each subject performed 12 trials per target object. Thus in total there were 60 trials per subject. These 60 trials were presented in a different random order for each subject.

Subjects were instructed to reach and grasp the target object at a natural movement speed using the index finger and thumb of their right hand, to lift it, and then put it back at the same location. To ensure that subjects grasped the target object by positions that were 6 cm apart they were instructed to grasp the ‘plus’ at the ends of the horizontal beam perpendicular to the main movement direction and to grasp the ‘block’ at the two vertical side edges. The subjects were also instructed to grasp the ‘cube’ by its side surfaces. This was necessary because grasping the cube by its front and back surfaces rather than by its left and right surfaces will, according to the grasping model of chapter 2, yield a different MGA for the same target object if collision avoidance is a major factor. Subjects began their grasping movement when they heard a verbal ‘go’ signal.

Movements were recorded at 100 Hz with an Optotrak 3020 motion recording system (Northern Digital, Waterloo, ON, Canada). Single infrared emitting diodes (IREDs) were attached to the nails of the subject’s index finger and thumb, and to the subject’s wrist (proc. styloideus ulnae).

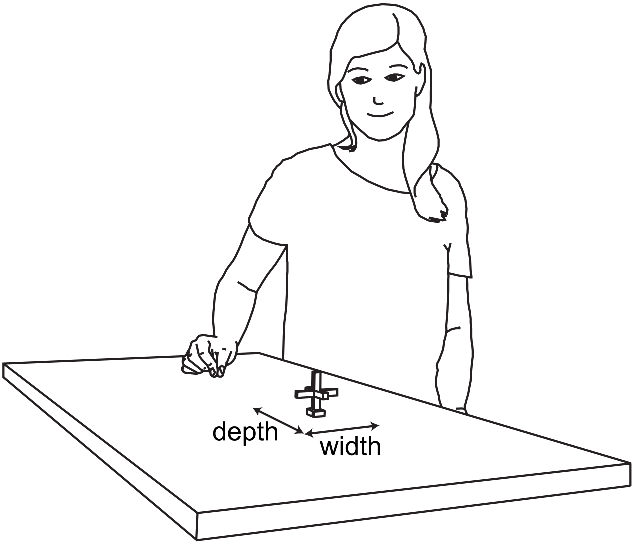

Fig. 7.1 The experimental setup (target object ‘plus’).

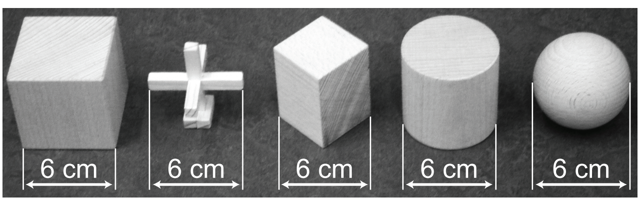

Fig. 7.2 Target objects. From left to right: ‘cube’, ‘plus’, ‘block’, ‘cylinder’, ‘sphere’.

Data analysis
The start of the grasping movement was defined as the moment at which the velocities of the tip of the thumb and the tip of the index finger both exceeded 0.1 m/s. The end of the grasping movement was defined using the Multiple Sources of Information method (Schot et al. 2010b). We used the criteria that both the index finger and thumb are within 30 mm of the target object's center in the depth-direction and less than 70 mm above the table, that the aperture is decreasing, that the second derivative of aperture is positive, that the mean of the velocities of the thumb and index finger is low (the objective function was 1 for zero velocity and decreased linearly to 0 for the maximum velocity), and that the movement time is short (the objective function was 1 for the start of the movement and decreased linearly to 0.8 for the last sample). We rejected the trial if the endpoint was not found using this paradigm or if there were more than two consecutive missing samples between the start and end of the grasping movement for the thumb, the index finger or the wrist. Together this resulted in the rejection of 14 of the 540 trials. Isolated or pairs of missing samples were reconstructed using linear interpolation.

In order to get an overview of the movement trajectories of the digits and of the wrist we constructed a top view of the trajectories by plotting the average sagittal-component against the average lateral-component. Because the number of samples varied across trials, we resampled the data of each marker for each trial such that each step corresponds to 1% of the path length of the concerning marker before averaging. We calculated the means of the resampled trajectories per subject, marker and target object and averaged these mean trajectories across the subjects.

To examine the influence of target object shape on MGA, we calculated the MGA for each trial as the maximum distance between the marker placed on the index finger and the marker placed on the thumb in the interval between movement start and movement end. We subsequently calculated for each subject the mean MGA per target object, and averaged these mean values across subjects. The effect of target object shape on MGA was tested using a one-way repeated measures analysis of variance (ANOVA).

Predictions

For collision avoidance we used model simulations to generate predictions (Chapter 2). The three other explanations are based on a single variable: desired precision, perceived width and perceived volume. In order to predict the MGA for the various target objects for each of these three explanations, we quantified the relevant variables for each target object on a scale that was normalized so that the value for the relevant variable was 1.0 for the cube. Based on these normalized values and the MGA that was found for the cube, we predicted the MGA for the other four target objects. The details of this method are explained in the remainder of this subsection.

Normalized desired precision

Assuming that our subjects succeeded in achieving the desired precision, desired precision is reflected in the variance of the digits' endpoints. We therefore determined the variance of the experimentally observed endpoints of the thumb and index finger, and calculated the desired precision per subject and condition as:

$$\text{Desired precision} = \frac{1}{\sigma_{SI}^2 + \sigma_{HI}^2 + \sigma_{ST}^2 + \sigma_{HT}^2}$$

In which σ_{SI}^2 is the variance of the final positions of the index finger in the sagittal direction, σ_{HI}^2 is the variance of the final heights of the index finger, σ_{ST}^2 is the variance of the final positions of the thumb in the sagittal direction and σ_{HT}^2 is the variance of the final heights of the thumb. The normalized desired precision was calculated per subject by dividing the desired precision for each condition by the desired precision for the 'cube'.

Collision avoidance

To evaluate how collision avoidance is reflected in behavior, we used the grasping model of chapter 2 in which the objective of collision avoidance is implemented. In this model two point masses, representing the tips of the index finger and the thumb, move in a force field. We will refer to these points as 'tips'. The force field is the sum of multiple forces that each represent one or two objectives that hold for each tip.

To make sure that the model's predictions are not due to fine-tuning of the model's parameters to the particular target object shapes used in the grasping experiment, we used the same values for the parameters A, R_o, K, E and D as in chapter 2 (Table 2.1). In chapter 2 the values for the parameters were chosen such that the simulated kinematics were in line with the experimentally found kinematics in a study of Jeannerod (1981). The parameter A sets the strength of the objective to arrive at the preselected goal position. The parameter R_o sets the strength of the objective to avoid collision with obstacles or positions on the target object other than the goal position. The parameters K and E set the strengths of the objectives to prevent collisions between the tips and limit the distance between the tips. The parameter D sets the strength of the objective to move smoothly and arrive simultaneously with both tips.

One of the objectives originally implemented in the model was that humans avoid collisions between their digits and the table's surface. This objective mainly caused the vertical curvature of the predicted movement. It did so to an extent that is set by the parameter R_t. In this chapter we changed the value of R_t to zero because we experimentally found that the table does not affect the vertical curvature, but that the curvature is mainly caused by local constraints at the start of the movement (Chapter 3). In line with that finding, we added an upward 'force' of 4 m/s^2 to the force field if the tip was lower than 5 mm. These values (4 m/s^2 and 5 mm) and the abrupt transition between the force being active and no longer being active (instead of a gradually changing force) are rather arbitrary. Since the quantitative model predictions will depend on the values for the parameters and we do not claim to use the most appropriate set of parameters, we are primarily interested in the model's qualitative predictions.

For the model simulations, the target object's dimensions and its position relative to the starting position were set in accordance with the experimental setup. The locations of the goal positions, to which the tips are attracted, are given as an input to the model. For each target object the goal positions for the tips were chosen based on the experimentally observed final positions of the digits, averaged across subjects. These experimentally found positions were not located exactly on the target object's surface because the markers were attached to the nails, so that the digits were between the markers and the target objects. We corrected for this using the knowledge of the experimental geometry.

Normalized perceived width

We determined the perceived width of the five target objects used in the grasping experiment by asking fifty naive subjects (32 females, 18 males) ranging in age from 18 to 73 years (mean=25 years, SD=12 years) to quantify the perceived width of each target object. None of the subjects had participated in the grasping experiment. We tested different subjects because asking the same subjects to judge the perceived width before the grasping experiment would direct their attention to perceived width, and asking them to judge the width after they grasped the objects would give them additional information about the target objects' widths from having grasped the objects.

The five target objects were each presented once, in a random order, at the same position relative to the subject as in the grasping experiment. The subjects were not allowed to touch the target objects. To quantify the perceived width the subject could either use an existing unit or a self-chosen unit that scaled linearly with perceived width. The normalized perceived width was calculated per subject by dividing each of the five reported values by the value reported for the 'cube'.

Normalized perceived volume

We determined the perceived volume of the five target objects used in the grasping experiment by asking fifty naive subjects (27 females, 23 males) ranging in age from 18 to 58 years (mean=31 years, SD=9.6 years) to quantify the perceived volume of each target object. None of the subjects had participated in the grasping experiment or in the experiment in which the width had to be judged (for the same reasons as those given in the section 'Normalized perceived width').

The five target objects were each presented once, in a random order, at the same position relative to the subject as in the grasping experiment. The subjects were not allowed to touch the target objects. To quantify the perceived volume the subject could either use an existing unit or a self-chosen unit that scaled linearly with perceived volume. The normalized perceived volume was calculated per subject by dividing each of the five reported values by the value reported for the 'cube'.

From various values to predictions

The normalized values for desired precision, perceived width and perceived volume were converted into predictions for the MGA in cm (per subject and condition) using the following equation:

$$\text{Predicted MGA} = 0.8 \cdot 6 \cdot \text{normalized value} + 6.82$$

We multiplied the normalized value by 0.8 and 6 because in the literature it has been reported that MGA scales with target object size with a slope of around 0.8 (Smeets and Brenner 1999a) and the size (width) of the target objects that we used was 6 cm. We added 6.82 cm to ensure that the predicted MGA will be equal to the experimentally found MGA for the 'cube'. Our prediction for obstacle avoidance was not based on a normalized value. In order to have a perfect prediction for the cube, we subtracted the difference between the model's prediction for the MGA for the 'cube' and the experimentally found MGA for the 'cube' (0.34 cm) from all MGAs predicted by the model. These transformations made it possible to directly compare the relationships between measured and predicted effects of target object shape on MGA across the four explanations.

Testing the predictions

To examine to what extent the four explanations could account for the experimentally found influence of target object shape on MGA we first calculated the mean of the predicted MGA per explanation, subject and target object, and then averaged these mean values across subjects. For collision avoidance this averaging was not done because the model of chapter 2 only predicts one value for the MGA per target object. Next, the squared correlation coefficient (r^2) between the experimentally found mean MGAs and the predicted mean MGAs was calculated per explanation. Note that the value of the correlation coefficient neither depends on the predictions being precise nor on the slope of the relationship. The larger r^2 the better the explanation accounts for the experimentally found dependence of MGA on object shape.

Results

The top view of the average movement trajectories suggests that there was a difference in MGA between the target objects (Fig. 7.3). A one-way repeated measures ANOVA showed that there was indeed a significant effect of target object shape on MGA ($F(4,32)=30.0$, $p<0.001$). Post-hoc comparison showed that the

MGA was significantly larger for the ‘cube’ than for all other target shapes (all $p<0.01$), the MGA was significantly smaller for the ‘sphere’ than for all other target shapes (all $p<0.01$), and that the MGA did not differ significantly between the ‘plus’, the ‘block’ and the ‘cylinder’ (all $p>0.6$). The squared correlation coefficient between the mean predicted MGAs and the experimentally found mean MGAs was highest for collision avoidance (0.76), lowest for desired precision (0.09) and had intermediate values for perceived width (0.29) and perceived volume (0.33) (Fig. 7.4).

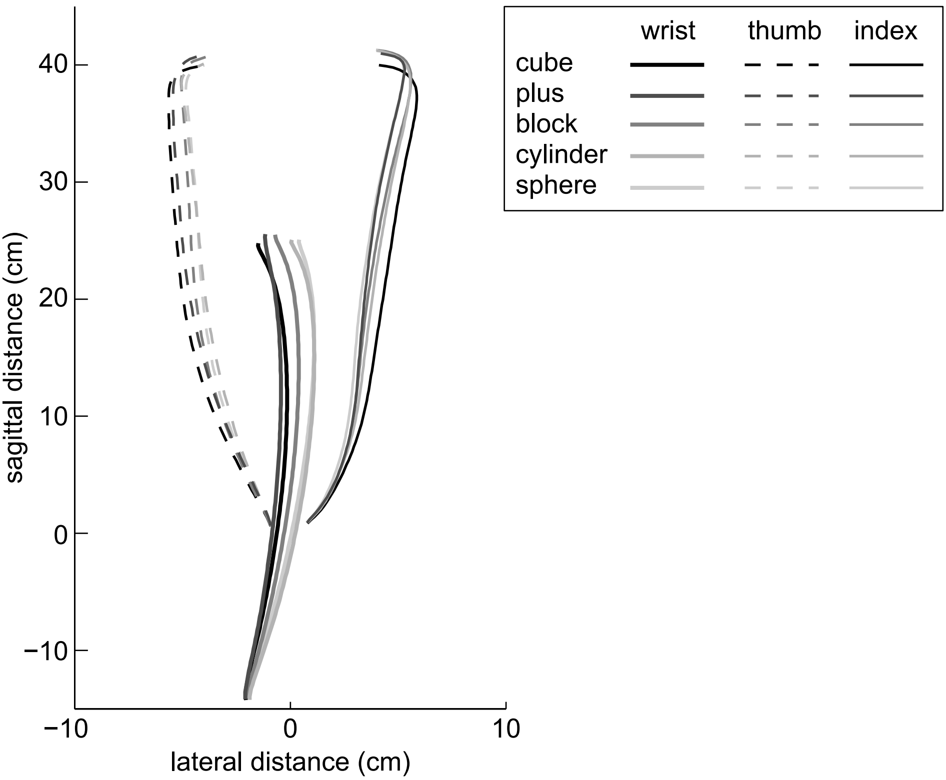

Fig. 7.3 Top view of the average trajectories of the wrist (proc. styloideus ulnae), the thumb and the index finger per target object.

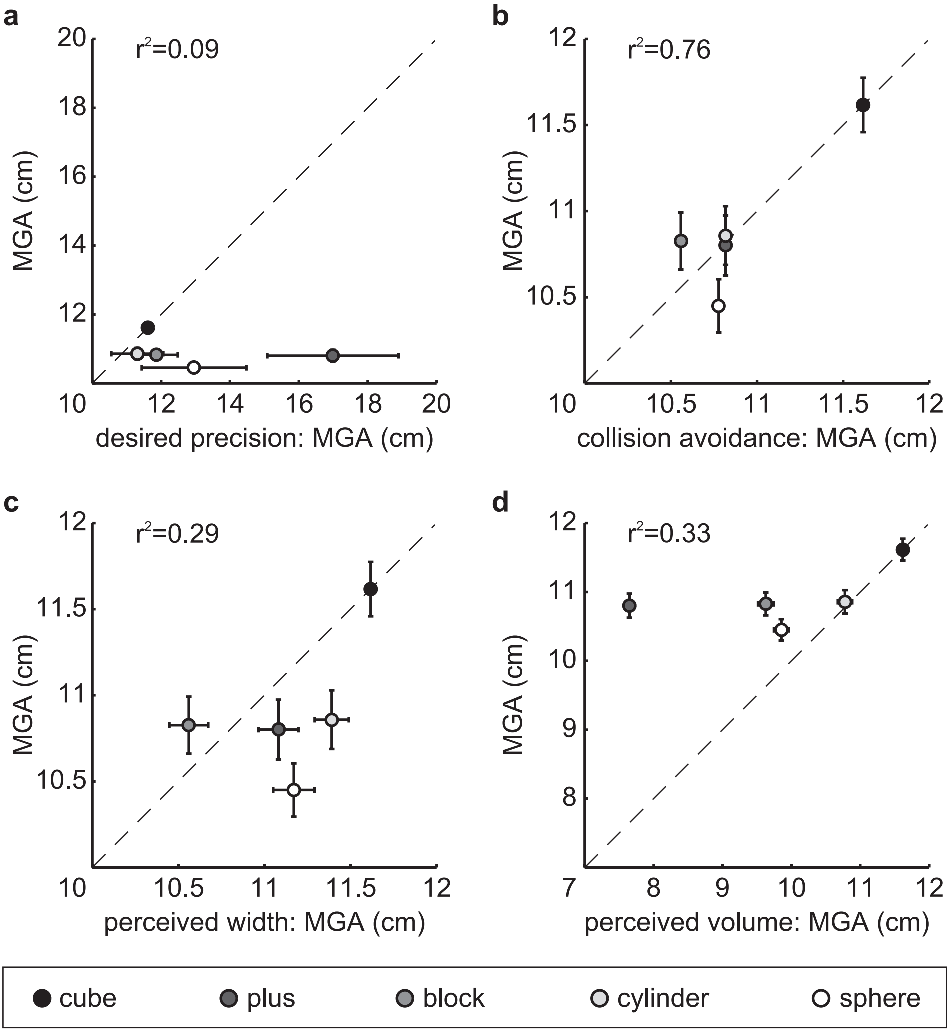

Fig. 7.4 Experimentally measured maximum grip aperture (MGA) as a function of predicted MGA for each of the four proposed explanations: a) desired precision, b) collision avoidance, c) perceived width, d) perceived volume. Note that the axes differ between the panels. Values are averages across subjects for each target. Error bars indicate the associated standard errors (and are only visible if larger than the radius of the point). Points on the dashed line indicate that the experimentally measured MGA is equal to the predicted MGA. The way we make the predictions ensures that this is always the case for the 'cube'.

Discussion

We aimed to get more insight into how target object shape influences MGA. In the introduction we mentioned that the desired precision of the digit's final positions ('desired precision', Smeets and Brenner 1999a), avoiding collisions between the digits and other parts of the target object than the goal positions ('collision avoidance', Cuijpers et al. 2004; Chapter 2; Chapter 6), and relying on perceived target object width ('perceived width', Franz et al. 2000; Franz 2001; Franz et al. 2001) or volume ('perceived volume', Chapter 6) might all contribute to the influence of target object shape on MGA. We examined the relative importance of these four explanations by performing an experiment for which the expected outcome differed between these explanations. In our experiment subjects grasped five differently shaped target objects with the same maximal width, height and depth, with the same final grip aperture. We used a 'cube', a 'plus', a 'block', a 'cylinder' and a 'sphere'. We found that MGA was largest for the 'cube' and smallest for the 'sphere'. There was no significant difference in MGA between the 'plus', the 'block' and the 'cylinder'.

To quantify the desired precision we calculated the precision of the experimentally found endpoints of the digits. To get an estimate of the effect of collision avoidance on MGA we simulated our experiment with the model of chapter 2. To quantify the perceived width and the perceived volume we performed separate experiments in which subjects judged the width and volume of the five target objects that were used in the grasping experiment. Based on theses values we then predicted the MGA and calculated the squared correlation coefficient between the experimentally found and the predicted mean MGAs per explanation. The squared correlation coefficient was highest for collision avoidance, lowest for desired precision and intermediate for perceived width and perceived volume. From the four explanations tested, collision avoidance can therefore best account for the experimentally found effects of target objects shape on MGA. Consequently, variations in desired precision and misperceiving width or volume are unlikely to play major roles in shape-related variations in MGA.

For desired precision, perceived width and perceived volume the predicted MGAs were calculated by multiplying the normalized values of the concerning factor with a constant and adding another constant. If we would have used other values for the constants or would have used the normalized values directly to calculate the squared correlation coefficients, the values for the squared correlation coefficients would have been exactly the same. Likewise, not subtracting a constant from the MGAs predicted by the model would not have effected the value of the squared correlation coefficient for collision avoidance. Our choice to let the predicted MGA for the 'cube' be equal to the experimentally found MGA for the 'cube' and our choice of the strength of the relation between MGA and desired precision, perceived width or perceived volume is therefore irrelevant for our conclusion that collision avoidance can account best for the experimentally found effects of target objects shape on MGA. It only makes the plots in figure 7.4 easier to interpret.

The MGA found for the 'sphere' was small, and that for the 'block' large compared to the model predictions based on collision avoidance. The reason might be that humans are (in contrast with the model of chapter 2) more eager to avoid collisions with edges than with smooth surfaces, and therefore open their hand wider when grasping the 'block' (which is grasped at its edges), and less wide for the 'sphere' (which has no edges).

In sum, this study supports explaining the influence of target object shape on MGA, as found in the studies of Cuijpers et al. (2004), Hu et al. (1999), Borchers et al. (Chapter 6), and in this chapter, by humans having the objective to avoid collisions between the digits and positions on the target object other than the goal positions. We propose that the objective to avoid collisions between the digits and positions on the target object other than the goal positions plays an important role in explaining how target object shape influences MGA.